Experimental Study of Structure of Low Density Jet Impinging on Tilt Plate by LIF and PSP

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Abstract. The structure of low density jets impinging on a tilt plate is studied by hybrid use of LIF and PSP. The jet through an orifice flows into low pressure chamber of 0.12 Torr and impinges on to the tilt plate with angle from jet axis 45° or 60° or 90°. A horizontal plane including the jet axis is visualized by LIF of seeded Iodine molecule, scanning a laser beam along the jet axis. On the other hand, the pressure distribution on the tilt plate is visualized by PSP. In comparing the results of the two methods, the shock wave system is analyzed. Deformation of the Mach disk and the barrel shock are confirmed.

1. INTRODUCTION

The attitude control of space–crafts is executed by a jet thruster issuing gas into space. There are some possibilities that the jet interacts with a solar battery panel or a part of the space-craft, affecting the attitude control. It is desirable to elucidate the pressure field on the surface which interacts with the jet.

In this paper, the structure of a jet impinging on a tilt plate is studied by hybrid use of the laser induced iodine fluorescence (LIF) and pressure sensitive paint (PSP). The former clarifies the structures of the shock system in the jet and the latter makes it possible to visualize the pressure distribution on the plate. Comparing these results, the correlation between the pressure distribution and structure of the jet is clarified.

The LIF experiments are carried out by scanning of an argon-ion laser beam in a horizontal plane including the center line of the jet. Fluorescence from the iodine molecules seeded in the argon jet makes it possible to visualize the structure of the shock system.

The PSP experiments depend on the oxygen quenching of the luminescence from luminescent molecules. In this experiment, Platinum-Octaethylporphyrin (Pt-OEP) is used as luminescent molecules and silicon-polymer as a binder. The tilt plate is covered with the paint and illuminated by UV light of 380 nm in wave length. The luminescence from the plate is acquired by a CCD camera. To increase the pressure sensitivity of the paint, pure oxygen is employed as the working fluid of the jet. The acquired signal is processed by a computer.

2. FUNDAMENTALS

2.1 Theory of LIF

Under the conditions of the experiments of the gas-dynamic interest, the dissociation of the iodine molecules can be ignored. If the broad-band fluorescence from all excited levels is collected, it can be approximated that the rotational transfer among the excited states can be neglected and the excited states are lumped into a single energy level (two-energy level model[(1)]). Under these assumptions, the fluorescence intensity F of the iodine molecules induced by a broad band laser is given by

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$$F = C\bar{\nu}\frac{A_{ij}}{A_{ij}+Q}B_{ij}If_1N_{I_2} \tag{1}$$

where C is a constant including collection efficiency and Planck constant, $\bar{\nu}$ the mean frequency, A_{ij} the spontaneous emission rate, B_{ij} the stimulated emission rate, Q the collision quenching rate, I the intensity of the laser beam and N_{I_2} the number density of the iodine molecule. Furthermore, f_1 denotes the fraction of the ground state population which is in resonance with the laser. Since the factor $A_{ij}/(A_{ij}+Q)$ is a function of pressure and temperature, it is impossible to determine the number density distribution only from the measurement of the fluorescence intensity distribution. However, the location of the shock wave is determined by the radical change of the fluorescence intensity which is attributable to the sharp variation of the number density across the shock wave.

2.2 Theory of PSP based on the oxygen quenching

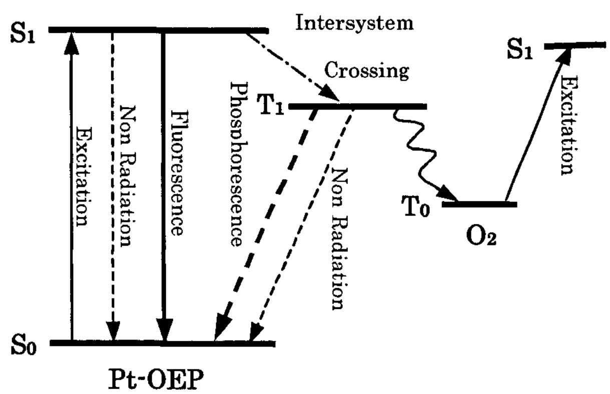

FIGURE 1. Energy Level Diagram of Luminescent molecules and Oxygen

Fig.1 shows the energy transfer in the luminescence molecules and quencher (oxygen) molecules. By the illumination of light, the luminescent molecules at the ground state (S_0) are transferred to an excited singlet state. In the condensed phase, the excited molecules fall to the lowest excited singlet state S_1 by the internal conversion. From S_1, the molecules may return to the ground state S_0 with or without emission of fluorescence. Another possibility is the transfer to a triplet state T_1 by the inter-system crossing. If there is no quencher molecule, the molecules at T_1 return to the ground state with emission of phosphorescence. By the existence of the quencher molecules, there are two possibilities of quenching[2]: (1) by an exchange of electron between the luminescent molecule at the excited singlet state S_1 and an oxygen molecule at the ground triplet state T_0, the luminescent molecule returns to the ground state S_0 and the oxygen molecule converts to the excited singlet state S_1. (2) by exchange of an electron between the luminescent molecule at T_1 state and oxygen the molecule at T_0 state, the luminescent molecule returns to the ground state S_0 and the oxygen molecule converts to the excited state S_1.

The rate of these quenching depends on the rate of encounters between the luminescent molecules and the oxygen molecules. When the number density of the luminescent molecules is fixed, the quenching rate depends on the partial pressure of oxygen p_{o_2}. Relation between intensity of luminescence I and p_{o_2} is given by the Stern-Volmer equation:

$$\frac{I_0}{I} = 1 + K(T)p_{o_2} \tag{2}$$

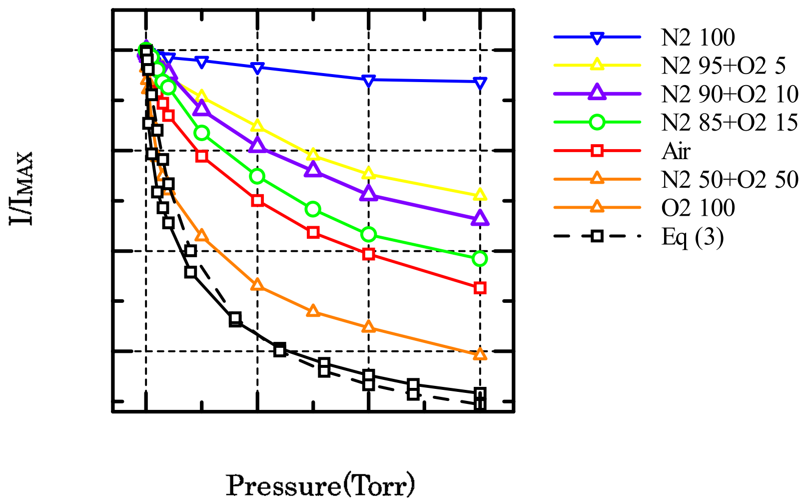

FIGURE 2. Dependence of luminescence intensity on pressure for various concentration of Oxygen and Nitrogen

where I_0 is the intensity of luminescence when $p_{o_2} = 0$ and K is a constant which depends on temperature.

When the concentration of the quencher in the working fluid is r, the partial pressure p_{o_2} is expressed in terms of the total pressure p of the working fluid which is usually measured in the aerodynamic experiments, i.e.

$$p_{o_2} = rp .$$

And Eq.(2) is rewritten as

$$\frac{I}{I_0} = \frac{1}{1+rKp} . \tag{3}$$

The dependence of the sensitivity of luminescence on the total pressure is given by

$$\left|\frac{\partial I}{\partial p}\right| = rK\left(\frac{1}{1+rKp}\right)^2 . \tag{4}$$

This shows the adequacy of the use of PSP in the low pressure range and the larger the concentration of the quencher is, the larger is the pressure sensitivity.

Fig.2 shows the experimental results for various concentrations of the quencher (oxygen) in the working fluid which is the mixture of nitrogen and oxygen. This results justify the use of pure oxygen (r=1) for the low pressure gas flow.

3. EXPERIMENTAL APPARATUS AND METHOD

3.1 LIF

Fig.3 shows the schematic diagram of the experimental apparatus of the LIF experiment. Iodine molecules are mixed with the working fluid (argon) in the mixing chamber and the mixture is supplied into the high pressure chamber ($p_h = 1000$ Torr), issuing into the vacuum chamber ($p_l = 0.12$ Torr) through an orifice of 0.3 mm in diameter. The free jet impinges on a tilt plate with an angle of 45°, 60° and 90° from the center line of the jet. The distance between the orifice and the plate along the center line is set at 15, 20 and 25 mm.

An argon-ion laser beam of wave length 514.5 nm with diameter of 0.6 mm is scanned in the horizontal plane including the center line of the jet. Fluorescence of the iodine molecules makes it possible to visualize the interacting jet. A camera attached with a telescope lens and a bellows is set normal to the scanning plane. Scanning of the laser beam is carried out by the motion of a mirror set on a x-stage which is controlled by a computer.

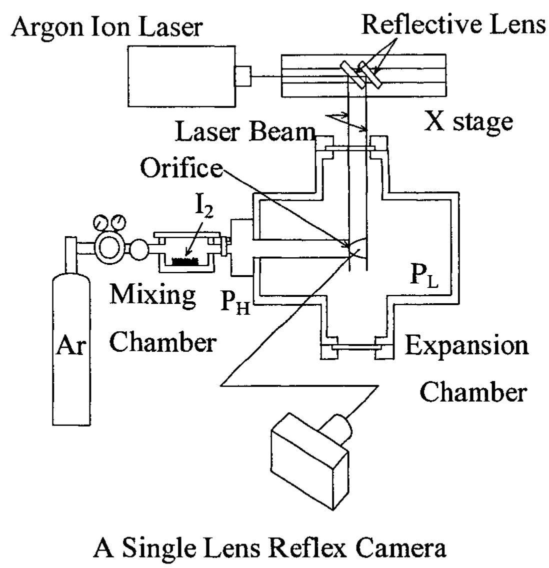

FIGURE 3. Experimental apparatus of LIF

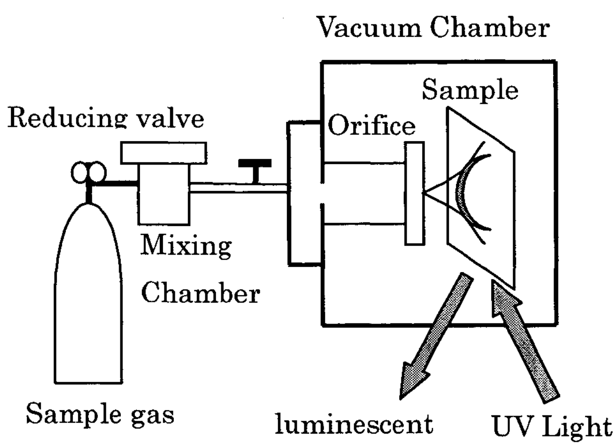

FIGURE 4. Experimental apparatus of PSP

3.2 PSP

Pt-OEP is used as the luminescent molecule which is dissolved in a layer of silicon-polymer as a binder. The surface of the tilt plate is covered by the paint and illuminated by light of 380 nm in wave length from a xenon-lamp with a narrow band-pass filter. The luminescence from the paint is acquired by a CCD camera and the signal is processed by a computer.

The error due to the non-uniformity of the paint and the non-uniform illumination is calibrated by dividing the luminescence signal of each pixel by the corresponding signal taken without flow.

The flow system is the same as that of LIF experiment except the supply of the mixture of argon and iodine is replaced by pure oxygen (Fig.4).

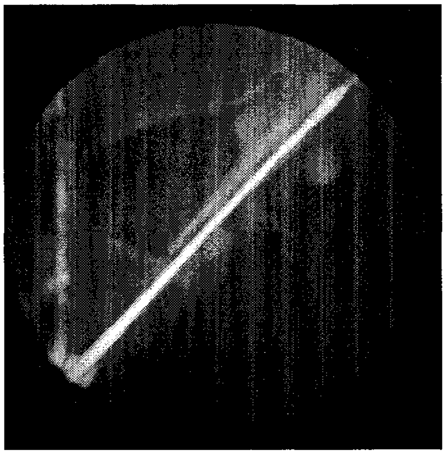

FIGURE 5-a. Flow Visualization by LIF, $\theta = 45°$, X_P=15mm

FIGURE 5-b. Visualization of pressure field by PSP, $\theta = 45°$, X_P=15mm

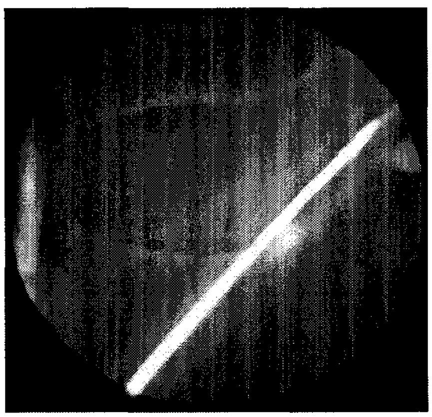

FIGURE 6-a. Flow Visualization by LIF, $\theta = 45°$, X_P=25mm

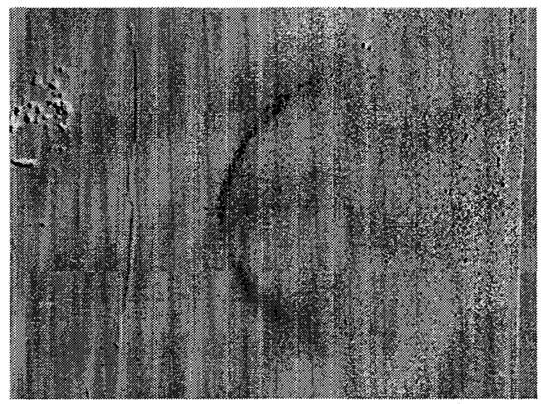

FIGURE 6-b. Visualization of pressure field by PSP, $\theta = 45°$, X_P=25mm

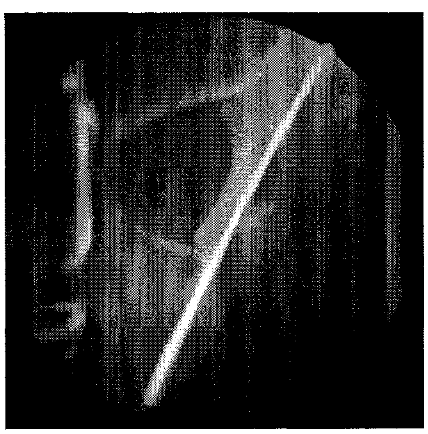

FIGURE 7-a. Flow Visualization by LIF, $\theta = 60°$, X_P=15mm

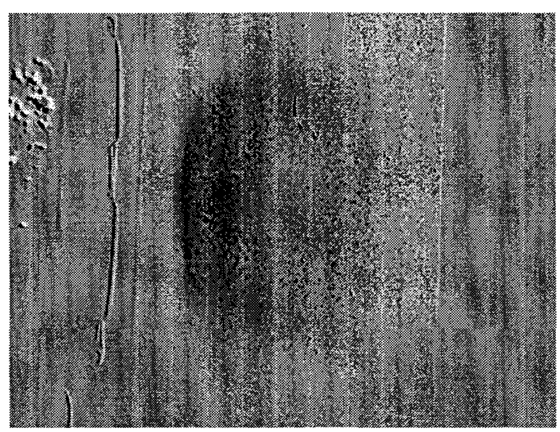

FIGURE 7-b. Visualization of pressure field by PSP, $\theta = 60°$, X_P=15mm

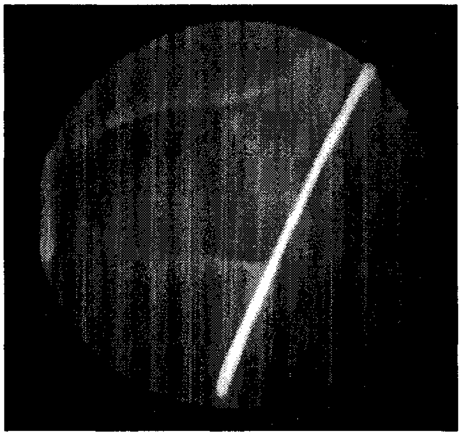

FIGURE 8-a. Flow Visualization by LIF, $\theta = 60°$, X_P=25mm

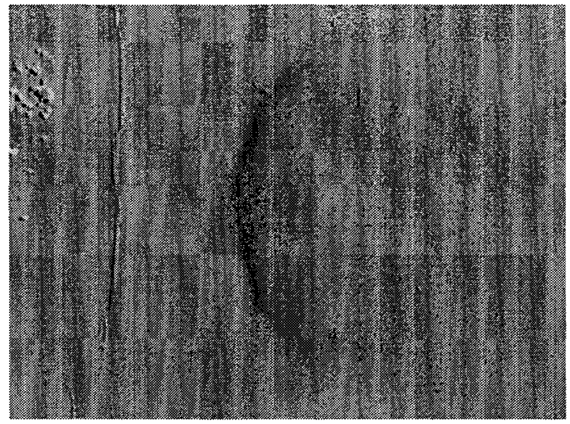

FIGURE 8-b. Visualization of pressure field by PSP, $\theta = 60°$, X_P=25mm

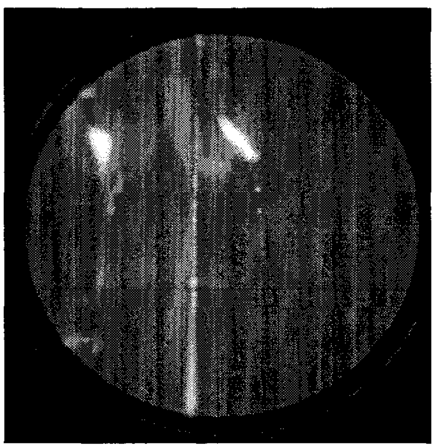

FIGURE 9. Flow Visualization by LIF, $\theta = 90°$, X_P=15mm

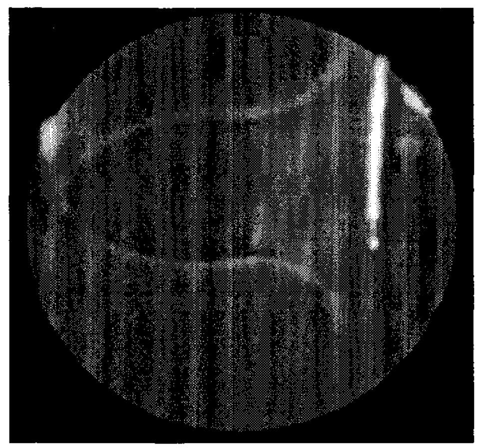

FIGURE 10. Flow Visualization by LIF, $\theta = 90°$, X_P=25mm

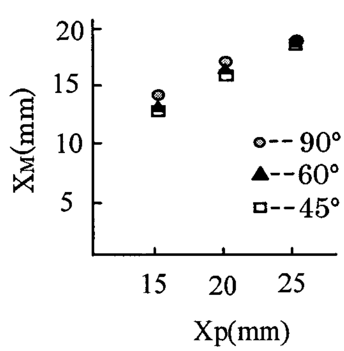

FIGURE 11. Relation between X_M and X_P

Note: Enlargement rate of Fig. 5 to Fig. 10 are different due to the difference of the position of the camera.

4. EXPERIMENTAL RESULTS

Fig's 5, 6, 7 and 8 show the photographs obtained by the LIF and PSP experiments. When the tilt angle θ is 45° and the distance between the orifice and the plate, X_p, is 15 mm, there is no large displacement of the Mach disk from its position in a free jet but it is divided sharply into two parts: one is almost normal and the other is oblique shock (Fig.5.a). In this case, pressure distribution shows a region of the high pressure due to the impingement of the barrel shock and due to the high pressure behind the oblique shock (Fig.5.b). When $X_p = 25$ mm, the Mach disk is almost not distorted from the shape in a free jet. When $\theta = 60°$ and $X_p = 15$ mm (Fig.7.a), general configuration of the shock system is similar to the case of $\theta = 45°$, but the Mach disk changes to a bow shape and the discontinuous bend disappears. Comparing the photograph of PSP image with that of the case for 45°, the image of the high pressure region is darker than the former case, showing a stronger interaction. As for the case of $X_p = 25$ mm, there is no distortion of the Mach disk, but the distance between the orifice and the Mach disk, X_M, along the center line is shorter than the case of 45°.

When $\theta = 90°$, $X_p = 15$ mm, $X_p = 25$ mm, the jet flows symmetrically with respect to the center line (Fig.9 and 10). The photograph of the pressure field for the case of $\theta = 90°$ is not taken because of the geometrical limitation of the illumination and detection system.

The distance of the shock from the orifice along the jet axis, X_M, is proportional to the distance between the orifice and the plate. The proportional constants of any tilt angles are the same (Fig.11).

5. CONCLUDING REMARKS

Structure of the shock system in a jet impinging on a tilt plate and pressure distribution on the plate are studied by a hybrid use of LIF and PSP. By comparison of these two methods, existence of high pressure region is explained in terms of the structure of the barrel shock and the Mach disk. The following conclusions are obtained:

(1) Pressure distribution on the tilt plate due to the impingement of a jet depends on the position of the plate relative to the position of the Mach disk in a free jet. When the plate is placed in front of the Mach disk, the high pressure region is generated by the impingement of the barrel shock and high pressure behind the oblique shock. When the plate is placed behind the Mach disk, the high pressure region becomes a semi-circle due to the impingement of the barrel shock.

(2) Use of pure oxygen as a working fluid in the low pressure range is effective to strengthen the pressure sensitivity of PSP.

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